

Assessing the potential of Multi-Model Topology Optimization for modular lightweight design of aircraft cabin structures

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Abstract

This paper investigates the potential of Multi-Model Topology Optimization (MMO) as a design support for modular lightweight aircraft cabin structures. Aircraft cabin components are characterized by high variety, frequent layout changes and strict mass, safety and certification requirements. These conditions create a pronounced conflict between modularization and lightweight design. Modular product architectures promote commonality and reuse but often lead to structural overdimensioning, whereas lightweight design produces highly load-case-specific solutions that are difficult to reuse across variants.

MMO is examined as a methodical approach to integrate both perspectives in an optimization process. By coupling multiple structural models through shared design variables, MMO enables the generation of common material distributions that remain applicable across different load cases, installation situations or geometric configurations. The study uses an adapted MBB beam as a simplified structural benchmark with a constant design space and three different load application points. Based on this setup, the influence of selected simulation parameters, including volume fraction, mesh resolution, minimum member size and SIMP penalization, is analyzed systematically. The resulting MMO designs are compared with corresponding Single-Model Optimization (SMO) results for individual load cases and with an SMO using a combined load case.

The results show that MMO can generate common load-path-oriented topologies with compliance values close to those of the combined-load-case SMO. At the same time, the study highlights the influence of parameter selection on topology quality, discreteness and compliance. Overall, the findings indicate that MMO offers potential for modular lightweight design problems in aircraft cabin development.

Keywords: MMO, product development, topology optimization, modular, product family

1. Introduction

Aircraft cabin structures represent one of the most variety-intensive subsystems in civil aircraft. Unlike primary airframe components, cabin elements and monument support structures are subject to frequent layout changes driven by airline-specific customization, evolving passenger expectations and regulatory requirements. These components must withstand multiple operational load cases while complying with strict mass, safety and certification constraints [1].

From a product development perspective, this results in a pronounced conflict between modularization and lightweight design. Modular design strategies aim to reduce development effort, certification cost and time-to-market through the reuse of standardized components across multiple aircraft variants. However, modular components must accommodate a wide range of load scenarios and installation conditions, which typically leads to structural overdimensioning [2, 3].

Lightweight design, in contrast, usually aims at an application-specific optimum. A structure optimized for one load case, one installation condition or one geometric configuration can achieve high structural efficiency, but it is often unsuitable for reuse in other variants. This leads to a fundamental conflict: modularity increases commonality of components but can reduce weight efficiency, whereas

lightweight design improves structural performance but may increase internal variety. In aircraft cabin development, this conflict is especially critical because additional mass directly affects fuel consumption and operational cost, while variant-specific development increases engineering and certification effort.

The challenge is therefore to identify methods that support modularity and lightweight design simultaneously rather than sequentially. Sequential approaches, such as first modularizing a product family and then optimizing selected modules for weight, often inherit the disadvantages of both perspectives. Similarly, first optimizing individual lightweight components and subsequently trying to standardize them across variants may lead to extensive redesign loops. A more suitable approach is the integrated development of common lightweight structures that are optimized from the beginning for multiple variants or load scenarios [4].

Multi-Model Topology Optimization (MMO) is an approach to integrate modularization and lightweight design within a single optimization process. By coupling multiple structural models through shared design variables, MMO enables the generation of compromise solutions applicable across several load scenarios and configurations [5]. This approach is particularly attractive for aircraft cabin structures, where modularity and weight efficiency are competing yet equally relevant objectives in early design phases.

Against this background, the present study investigates MMO as a design support method for modular lightweight aircraft cabin structures. The focus is not limited to demonstrating the feasibility of MMO, but extends to the systematic analysis of parameter sensitivity. While topology optimization and its parameter effects have been studied extensively for Single-Model Optimization, MMO remains less investigated. It is therefore unclear whether established SMO guidelines can be transferred to MMO or whether MMO requires its own parameter recommendations. The paper addresses this gap by comparing MMO and SMO results and by analyzing how selected simulation parameters influence topology and compliance.

2. State of the Art

The state of the art is structured around four perspectives relevant to MMO in aircraft cabin development: modular product architectures, modular lightweight design, topology optimization and Multi-Model Topology Optimization. Together, these perspectives explain the need for commonality, standardized interfaces and controlled internal variety, while also addressing the conflict between modular reuse and structural efficiency.

The following subsections connect product-development reasoning with numerical optimization. This is necessary because MMO must not only be evaluated by compliance, but also by its ability to generate reusable common topologies with acceptable structural performance, stable interfaces and reduced internal variety.

2.1 Modular product architectures and product-family design

Aircraft cabin structures are embedded in high variety product environments. Airlines demand individual cabin layouts, different monument positions, varying passenger-service configurations and changing equipment packages. From a product development perspective, this leads to a high degree of external variety, while aircraft manufacturers aim to keep internal variety in components, interfaces, documentation and assembly processes as low as possible. Modular product architectures address this challenge by decomposing products into modules with defined interfaces, allowing different product variants to be created by recombining common or standardized elements [6].

Product architecture describes the allocation of product functions to physical components and defines how these components interact through interfaces [7]. Within modular product families, this allocation is used strategically to enable high external variety while limiting internal component and process variety [8, 9]. For this reason, modularization is not only a geometric decomposition of a product but also a method for managing complexity, reuse and product-family scalability. The development of modular product families therefore requires the simultaneous consideration of technical-functional

relationships, product-strategic decisions and interface standardization [10].
A key benefit of modular product architectures is the possibility of reusing modules across several variants. This can reduce development effort, simplify documentation and stabilize certification-relevant knowledge. In aircraft cabin development, these benefits are particularly relevant because cabin products are operated over long life cycles and are subject to strict certification and safety requirements. If a structural module or interface can be reused across variants, redesign effort and variant-specific validation activities may be reduced.
However, modularity also introduces structural disadvantages. A module intended for multiple variants must usually withstand the most critical combination of load cases, installation positions and boundary conditions. As a result, modular components are often overdimensioned for less critical variants. This effect is especially problematic in aerospace engineering, where every additional mass contribution affects operational efficiency. Thus, modularization creates a conflict between reuse and weight efficiency.

2.2 Modular lightweight design in aircraft cabin structures

Lightweight design follows the objective of reducing structural mass while maintaining required stiffness and strength [11]. In aircraft structures, lightweight design is essential because mass influences fuel consumption, emissions and operating cost [12]. Conventional lightweight design often leads to application-specific solutions that are optimized for one defined load case or installation situation.
The conflict between modularization and lightweight design can therefore be described as a conflict between commonality and specialization. Modularization promotes reusable components and standardized interfaces but can lead to overdimensioning or performance compromises [13]. Lightweight design promotes load-path-oriented structures with minimum mass but tends to produce variant-specific components. This conflict has been identified as a central challenge in modular lightweight design, particularly for complex technical systems and aircraft cabin applications [4].
Modular lightweight design attempts to reconcile these opposing objectives by integrating lightweight principles into modular product-family development. Instead of first defining modules and subsequently reducing their weight, both modularity and lightweight performance should be considered simultaneously [14]. For aircraft cabins, this is relevant since these structures must often support different cabin layouts while remaining lightweight and certifiable.

2.3 Fundamentals of topology optimization

Topology optimization is a well-established computational method for generating material layouts within a defined design space. Instead of improving an existing geometry, topology optimization determines where material is required and where it can be removed. This makes the method particularly suitable for lightweight design in early development phases [15, 16].
Density-based topology optimization methods are widely used in structural optimization. In these approaches, the design domain is discretized into finite elements, and each element is assigned a density variable. A density value close to one represents solid material, while a density value close to zero represents void material. The optimization algorithm changes the density distribution iteratively in order to minimize an objective function, typically compliance, under constraints such as a maximum allowable volume [15, 17].
Compliance minimization is commonly used as a stiffness-oriented objective. Since compliance represents the work done by external loads, minimizing compliance is equivalent to maximizing structural stiffness for a given amount of material. The resulting topology reveals load paths and structural regions that are relevant for force transmission. This makes topology optimization especially useful for identifying efficient structural concepts before detailed geometric design is performed [18].
Although topology optimization is a powerful method, its results are sensitive to numerical settings. Several well-known numerical challenges have been identified in the literature, including

checkerboarding, mesh dependency, local minima and intermediate-density regions [19]. Checkerboarding describes alternating patterns of solid and void elements that can artificially increase stiffness in finite element models but do not represent physically meaningful structures. Mesh dependency means that different mesh resolutions can lead to different topologies under otherwise identical boundary conditions. Local minima can cause the optimization to converge toward different designs depending on the initial conditions and parameter settings.

Filtering and regularization techniques are commonly used to address these issues. Density filters and minimum length-scale approaches can reduce checkerboarding and mesh dependency by smoothing the density field or by enforcing minimum structural feature sizes [20, 21]. However, these techniques also reduce design freedom and can increase compliance. Therefore, the selection of filtering parameters must balance numerical stability, manufacturability and structural performance.

The volume fraction controls how much material may remain in the design space. Higher volume fractions usually reduce compliance because more material is available for load transfer. However, they also reduce lightweight potential. Low volume fractions can generate efficient truss-like structures, but they may also lead to thin members, disconnected regions or manufacturing difficulties [17, 18].

Mesh resolution determines the level of geometric detail that can be represented. A finer mesh can capture smaller structural features and more detailed load paths, but it increases computational effort. A coarse mesh may suppress relevant features and distort the resulting topology. Therefore, mesh convergence or at least mesh sensitivity should be considered when interpreting topology optimization results [19].

The minimum member size defines the smallest allowable structural feature. It is useful for avoiding unrealistically fine structures and improving manufacturability. However, if the minimum member size is too large relative to the design space or mesh resolution, it can prevent the formation of efficient load paths. This can lead to higher compliance or diffuse material distributions [22, 23].

The Solid Isotropic Material with Penalization (SIMP) method is a common density-based approach. The SIMP penalty factor directly influences the treatment of intermediate densities. A higher penalty factor reduces the effective stiffness contribution of intermediate-density elements and thereby promotes more discrete topologies. However, excessive penalization can worsen convergence behavior or increase sensitivity to local minima. Parameter studies have shown that different combinations of topology optimization parameters can have significant effects on topology quality, structural strength and computational cost [24, 25].

2.4 Multi-Model Topology Optimization

MMO extends conventional topology optimization by enabling the simultaneous optimization of multiple structural models using shared design variables within a single optimization framework [26, 27]. Instead of optimizing one model for one set of boundary conditions, MMO links multiple models through corresponding density variables in shared design regions. These coupled variables enforce a common material distribution across all considered models. MMO is therefore particularly applicable when similar structures must be designed for different configurations, assemblies or boundary conditions, for which case-specific optimizations would yield limited reusability [28]. This distinguishes MMO from conventional Single-Model Optimization (SMO) and from multiple-load-case optimization. In a conventional SMO, one model is optimized for one load case or one combined set of load cases. In multiple-load-case optimization, several loads act on the same model. This is suitable when all relevant loads can be represented within one geometric configuration and one set of boundary conditions.

Figure 1 illustrates the fundamental concept of MMO.

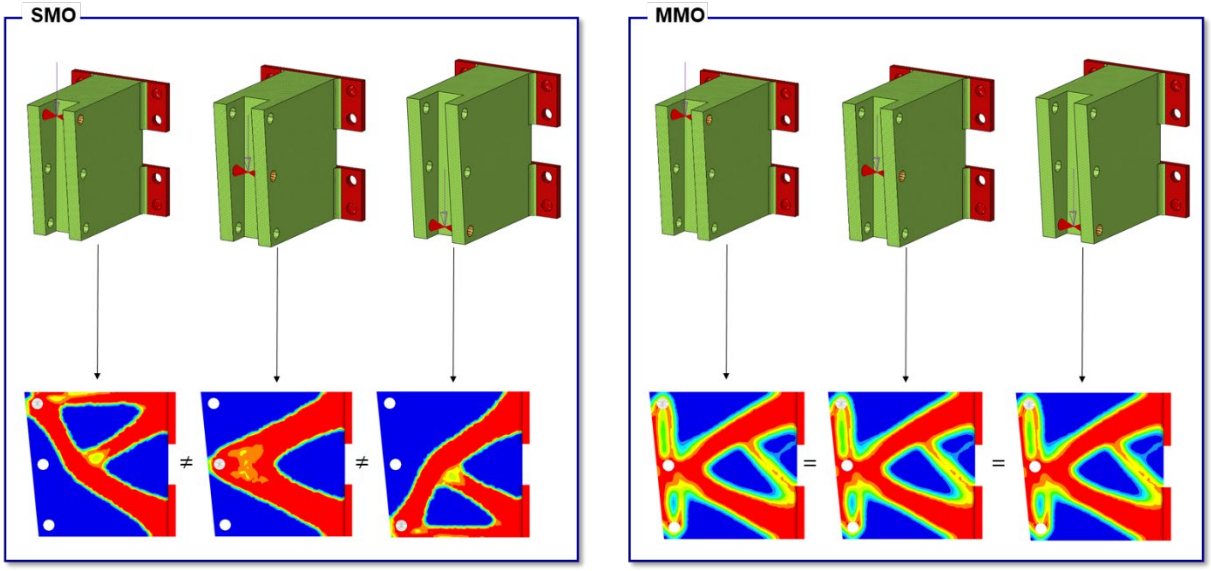


Figure 1 – Comparison of SMO and MMO based on one component loaded by 3 different forces

Figure 1 compares single-model optimization (SMO) and MMO for one component subjected to three different force application points. The left side shows the SMO results, where each model is optimized separately for one specific load case. This leads to different optimized topologies for the same component. The right side shows the MMO results, where the design regions of all three models are linked through corresponding density variables. As a result, an identical topology is obtained for all load cases. This enables the common use of the component across different loading conditions and supports component commonality in modular design.

2.5 MMO as an enabler for modular lightweight aircraft cabin design

Aircraft cabin structures represent a suitable application field for MMO because they combine high variety with strict lightweight requirements [1]. Typical cabin structures must accommodate changing monument positions, different interface loads and layout-dependent installation situations. At the same time, manufacturers aim to standardize components and interfaces in order to reduce internal variety and certification effort. MMO can support this design challenge by identifying structural regions that can be shared across variants [4]. For example, if several cabin configurations require a similar support structure with different load introduction points, MMO can be used to generate a common topology that satisfies all configurations.

In addition, MMO can support modular architecture development by indicating whether structural commonality between different configurations is feasible. If several configurations can be combined in an MMO with acceptable performance loss and a clear material distribution, this indicates that a common structure or standardized interface may be feasible. If the MMO result shows excessive compliance, strong intermediate-density regions or unstable topology behavior, this may indicate that the considered variants are structurally incompatible and should instead be separated by variant-specific modules or adapter concepts [4].

This interpretation is particularly relevant in early design phases. At this stage, design decisions about interfaces and modular architectures have a strong influence on later development effort. MMO can provide structural feedback based on simplified design spaces, preliminary boundary conditions and abstracted load cases before detailed component geometries and certification-level analyses are developed. It therefore complements methodical modular product-family development by adding a structural optimization perspective.

2.6 Research gap

Topology optimization is well established for lightweight structural design, and the influence of parameters such as volume fraction, mesh resolution, filters and penalization has been studied extensively for SMO. However, the transferability of these findings to MMO is not yet sufficiently understood. MMO introduces additional constraints because several models are coupled through shared design variables. This coupling can influence topology formation, compliance and the occurrence of intermediate density values, so that parameter effects known from SMO cannot be assumed to be directly transferable without further investigation.

While parameter effects in SMO are well documented, the systematic parameter sensitivity of MMO has received less attention. Existing MMO studies demonstrate the feasibility of generating common topologies across multiple models, but predominantly focus on qualitative comparisons or application-driven examples [26, 27]. Consequently, there is still limited knowledge on how selected simulation parameters affect the quality of MMO results in terms of topology, compliance and discreteness. In particular, it remains unclear which parameter settings support the generation of sufficiently discrete and structurally efficient common topologies in an MMO setup.

The research gap addressed in this paper is therefore the lack of a systematic assessment of how selected topology optimization parameters influence MMO results and how these results compare with corresponding SMO references. This is particularly relevant for modular lightweight aircraft cabin structures, where the optimization result must not only achieve low compliance, but also support commonality and reuse across different load scenarios.

For modular lightweight design, MMO offers a promising possibility. It can generate common load-path-oriented structures that are not individually optimal for one variant but applicable across multiple variants. The result is therefore a compromise topology. Such a topology may show higher compliance than individual SMO results, but it can provide higher commonality, reduced internal variety and improved reuse potential.

This changes the interpretation of optimization performance. An MMO result should not be judged only by whether it reaches the compliance of an individual SMO result. Since each SMO is optimized for one specific scenario, it represents a case-specific optimum. MMO intentionally sacrifices part of this individual optimum in order to obtain a reusable common solution. Therefore, MMO must be evaluated using additional criteria such as commonality, discreteness, and relative performance loss.

Based on this gap, the following research question is addressed: How do selected topology optimization parameters influence the topology, compliance and discreteness of MMO results, and to what extent can MMO support the generation of reusable common lightweight structures with acceptable performance loss compared with corresponding SMO references?

3. Methodology

3.1 Research design

This section describes the methodological approach used to evaluate the influence of simulation parameters on MMO. The study is based on a simplified structural benchmark that enables a systematic comparison between MMO and SMO under controlled boundary conditions. The use of an abstract model is intentional, since the objective is not the optimization of a specific aircraft component, but the identification of parameter effects that influence the quality, robustness and interpretability of MMO results.

Before defining the benchmark model, the methodological scope of the study is classified with regard to the applicability of different optimization approaches. The suitable method depends on whether the design space remains constant or varies between the considered variants, and whether one or several load scenarios have to be considered. An overview of the classification is presented in Figure 2.

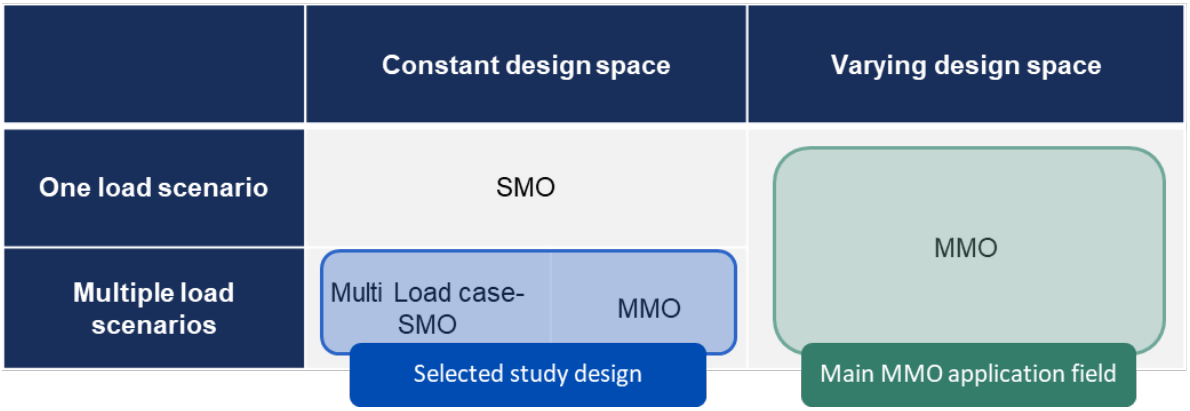


Figure 2 - Classification of optimization approaches according to design-space and load-case variety

For a constant design space and a single load scenario, SMO provides a case-specific optimum. If several load scenarios act on the same design space, either a multiple-load-case SMO or an MMO formulation can be applied. In contrast, if the design space varies between configurations, MMO becomes the relevant approach because corresponding design variables can be coupled across different structural models.
This distinction is important for the design of the present study. The main application potential of MMO lies in product-family contexts with varying design spaces. However, such cases do not allow a direct comparison with SMO, since no single reference model exists that represents all configurations simultaneously. For this reason, the present study deliberately focuses on the intermediate case of a constant design space with multiple load scenarios. This setup enables the calculation of individual SMO reference solutions for each load scenario while still allowing the same scenarios to be combined in an MMO.
The selected study design therefore provides a controlled basis for investigating parameter sensitivity. By keeping the design space constant, changes in the optimization results can be attributed primarily to the varied simulation parameters rather than to geometric differences between models. At the same time, the use of multiple load positions introduces the need for a common topology, which is the central methodological characteristic of MMO. This makes it possible to systematically analyze how parameters influence topology, compliance and density distribution.
The methodology follows three steps. First, individual SMO are performed for separate load positions in order to establish case-specific reference solutions. Second, the same load scenarios are combined in a MMO by coupling the corresponding design variables across the models. Third, selected simulation parameters are varied systematically to assess their influence on the resulting topology, compliance and density distribution. This setup makes it possible to investigate whether parameter effects known from SMO can be transferred to MMO.

3.2 Model setup and parameter variation

To investigate the influence of simulation parameters on the results of an MMO, simulations with varying simulation parameters are performed and the obtained solutions are compared with corresponding SMO results. For SMO, a large number of parameter studies already exist, demonstrating the sensitivity of optimization outcomes to the choice of initial parameters [19–21, 29]. Many of these studies are based on the Messerschmitt–Bölkow beam (MBB beam), which represents a two-dimensional beam with a length-to-height ratio of six and a centrally applied transverse load [30, 31]. Building on this established benchmark, the same example is adopted in this study to ensure comparability of results and to reduce computational effort.
Since an MMO requires different initial states, three distinct load application points are considered. One of them corresponds to the conventional central load case of the MBB beam, while two additional load positions represent shifted load introductions. The force amplitude is kept constant. This generates three structurally similar but not identical optimization problems that can be coupled in MMO. The schematic setup of the model is shown in Figure 3.

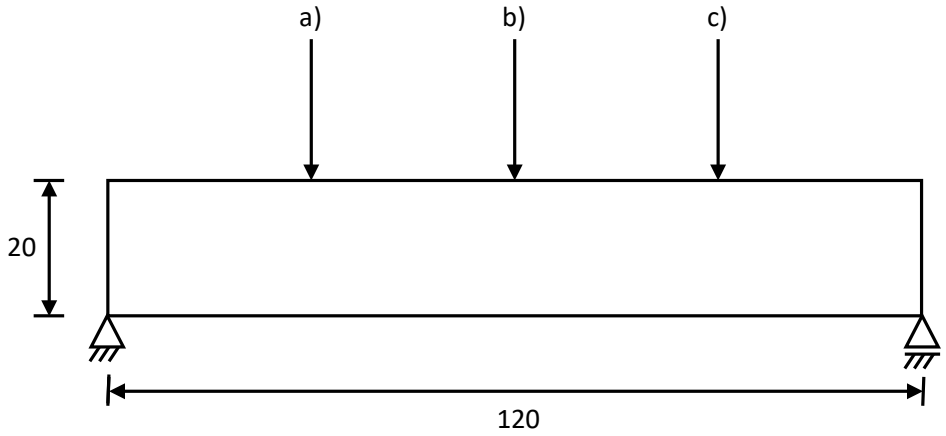


Figure 3 - Adapted MBB Beam used in this study

The simulation parameters considered and the corresponding variations in those parameters are summarized in *Table 1*. They refer to the adapted MBB Beam example [31]. These parameters were selected because they are known to influence SMO results and because they are directly relevant for the practical setup of topology optimization models.

Table 1 - Parameters considered for the systematic MMO study

Parameter	Investigated parameter ranges
Volume fraction	10 - 75 % (Δ = 1 %)
Minimum member size	1.5 - 5 mm (Δ = 0.1 mm)
Mesh resolution	0.2 - 1.0 mm (Δ = 0.1 mm)
SIMP penalty factor	P=1 - 10 (Δ = 0.2)

4. Results and Discussion

To analyze the influence of simulation parameters on the results of MMO, systematic parameter studies are conducted. Based on the adapted MBB beam, the effects of the volume fraction, mesh resolution, Minimum Member Size Control, and the SIMP penalty factor are investigated. Building on this, the combined effect of Minimum Member Size Control (MinDim) and the SIMP penalty factor is analyzed in a full factorial study. The identified parameter combinations are subsequently applied in an MMO and compared qualitatively and quantitatively with the results of an SMO. Finally, the influence of the simulation parameters on the MMO results is discussed.

4.1 Variation of the Volume Fraction

To investigate the influence of the volume fraction, the maximum allowable design volume of the MMO is varied. Figure 4 shows the qualitative results of the MMO of the MBB beam for volume fractions ranging from 10 % to 75 %. The color scale represents the normalized element density ρ, with high density values indicating material-filled regions and low-density values indicating void regions.

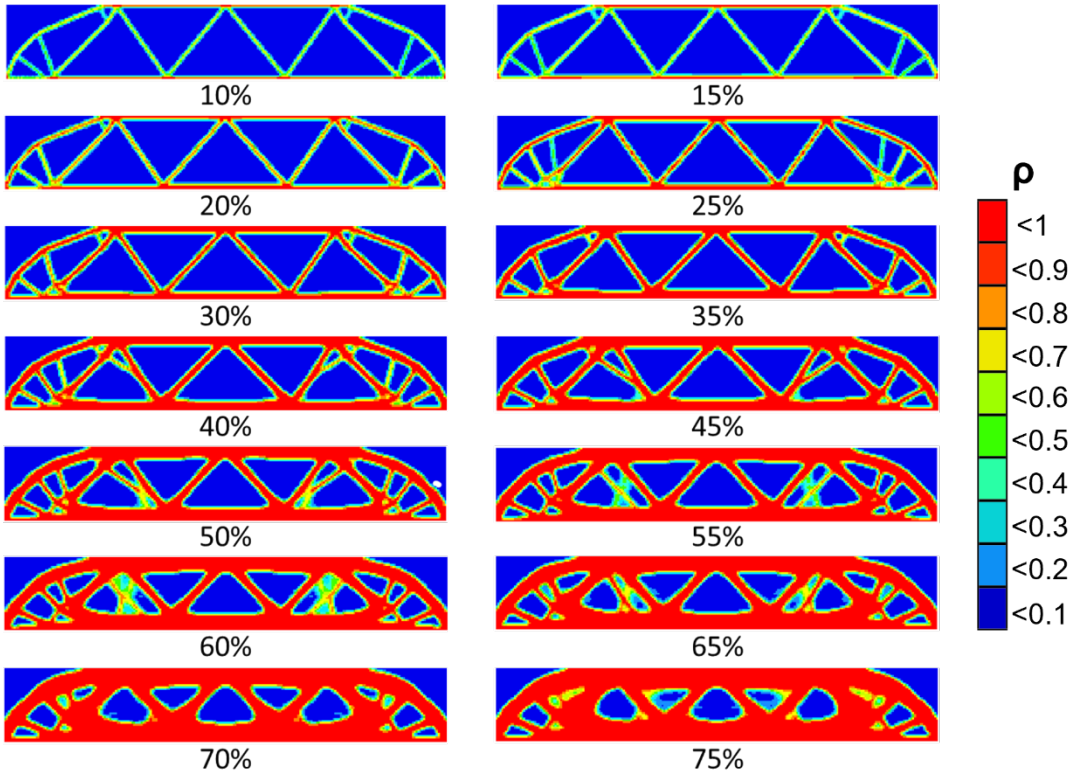


Figure 4 - Qualitative results of the MMO with variation of the volume fraction

At a volume fraction of 10 %, the high element densities are concentrated along the boundary regions of the structure. The load paths between the support and force application points consist predominantly of elements with density values below 0.6. Up to a volume fraction of 20 %, the available amount of material is too low for the selected simulation parameters to form continuous load paths with element densities close to 1 and, consequently, sufficiently discrete structures. The load paths with high element densities that are already visible at a volume fraction of 10 % become more pronounced as the volume fraction increases. At the same time, the proportion of elements with high density values increases, resulting in a progressively more massive load-bearing structure. In addition, the cross-sectional widths of the load-bearing struts increase and additional load paths are formed. From a volume fraction of 70 % onward, the proportion of high-density elements becomes so large that adjacent load paths merge and the structure increasingly develops into a plate-like configuration.
The compliance curve for the central load case (see Force b) in Figure 3) is shown in Figure 5. Compliance decreases monotonically and degressively as a function of the volume fraction. In the range of low volume fractions, changes in the volume fraction have a strong influence on compliance. This influence decreases with increasing volume fraction. From a volume fraction of approximately 30 %, a plateau begins to form, so that a further increase in the volume fraction leads only to a minor reduction in compliance.
Analogous to SMO, the volume fraction in MMO should be selected such that a compliance plateau is reached. This allows a compromise between stiffness improvement and material usage, since additional material above this volume fraction contributes only marginally to a further reduction in compliance.

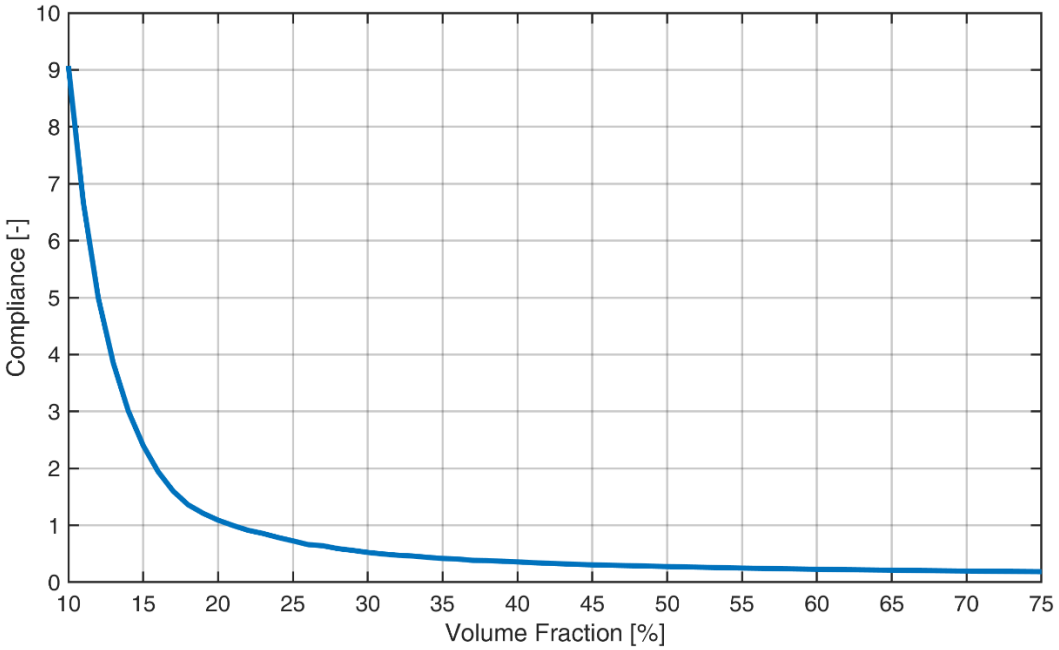


Figure 5 – Compliance of the MMO for force b) with variation of the volume fraction

4.2 Variation of Mesh Resolution

To investigate the influence of mesh resolution, the element size is reduced from 1 mm to 0.2 mm. Figure 6 shows the results of the MBB beam for the different element sizes, including the corresponding number of elements.

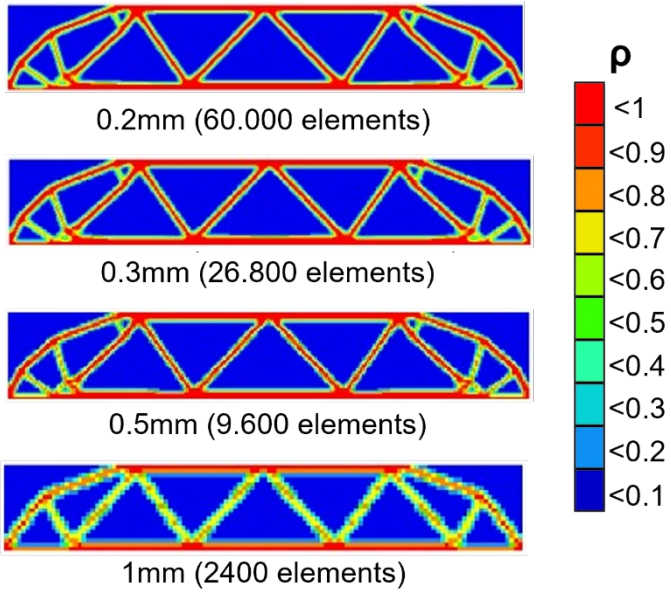


Figure 6 - MMO result with variation of the average element size

Across all investigated mesh resolutions, the fundamental topology remains nearly unchanged. In particular, the main load paths between the support and force application points as well as the characteristic truss-like structure are reproduced independently of the selected element size. The formation of a larger number of struts with increasing element number, which is typical for SMO [29], can only be observed between 1 mm and 0.5 mm. However, no additional struts are formed when the element size is further reduced. This may result from the MMO or the chosen example. Further investigation is needed. The finest resolution in the MMO study comprises approximately 60,000

elements. Compared with the models investigated in [29], however, the resulting structure shows a lower number of branches and struts. On the one hand, this may be attributed to the lower number of elements in the present study. On the other hand, it cannot be excluded that MMO itself influences the formation of additional struts, since the consideration of multiple load cases can lead to a different density distribution and, consequently, to reduced structural branching. Further investigation of this influence is still needed.
With increasing element size, the structural boundaries become less sharp, since the width of the transition regions with intermediate density values and the stair-stepping of the structural contour increase. At an element size of 1 mm, the main load paths also contain intermediate density values. In addition, the number of individual load paths decreases compared with an element size of 0.5 mm.

4.3 Variation of MinDim

The corresponding MMO results are shown in Figure 7, where MinDim is varied from 1.5 mm to 5 mm. Comparable results for SMO have been reported in [32].

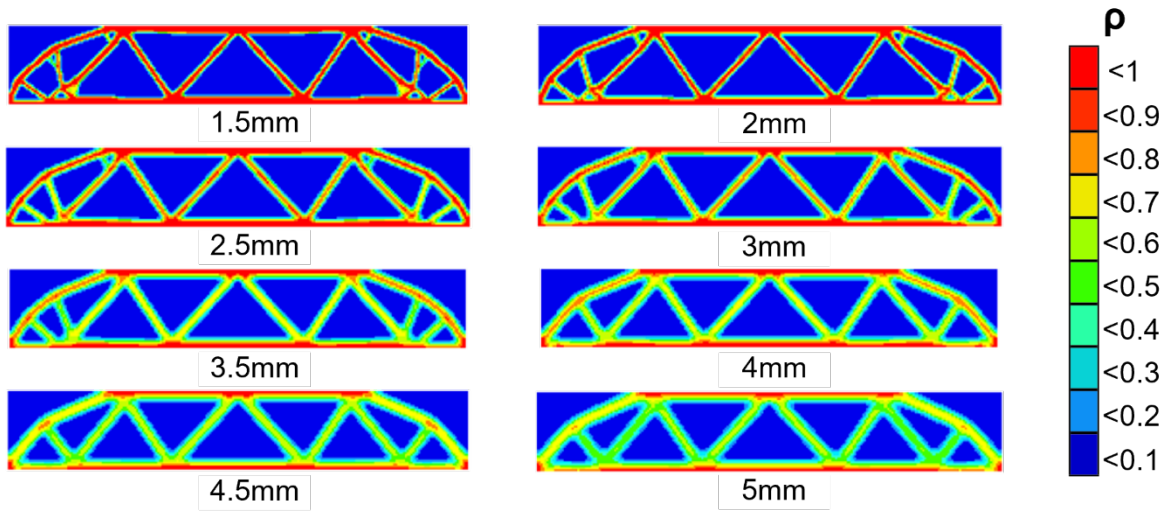


Figure 7 - Density distribution under varying MinDim for MMO

The results indicate that increasing MinDim leads to a growing number of elements with intermediate density values between 0.1 and 0.9, reflecting a deterioration of material distribution. This qualitative behavior is also typical for SMO; however, for MMO the effect occurs at significantly smaller minimum member sizes.
From a methodological perspective, the observed behavior indicates that MMO amplifies parameter interactions due to the coupling of multiple model configurations. As a result, parameter ranges that are commonly regarded as uncritical in SMO may already lead to degraded material distributions in MMO. When using an MMO, the MinDim parameter must be considered separately, as the parameter values recommended for an SMO cannot be directly applied to an MMO.

4.4 Variation of the Penalty Factor

The qualitative results of the study on the variation of the SIMP penalty factor are shown in Figure 8. It can be observed that the qualitative shape of the target design changes under strong variation of the penalty factor. Up to approximately P = 5, the basic structural layout remains similar, whereas from P = 7 onward, the target design changes into a completely different structure.
The compliance results for the variation of the penalty factor support the qualitative findings. Up to P = 5, compliance remains at an approximately constant level with a slight increase. From P = 7 onward, compliance increases sharply and shifts to a significantly higher level. At this level, compliance stabilizes again, but continues to oscillate strongly. The pronounced change in the target design from P = 7 onward is therefore also reflected in the compliance results.

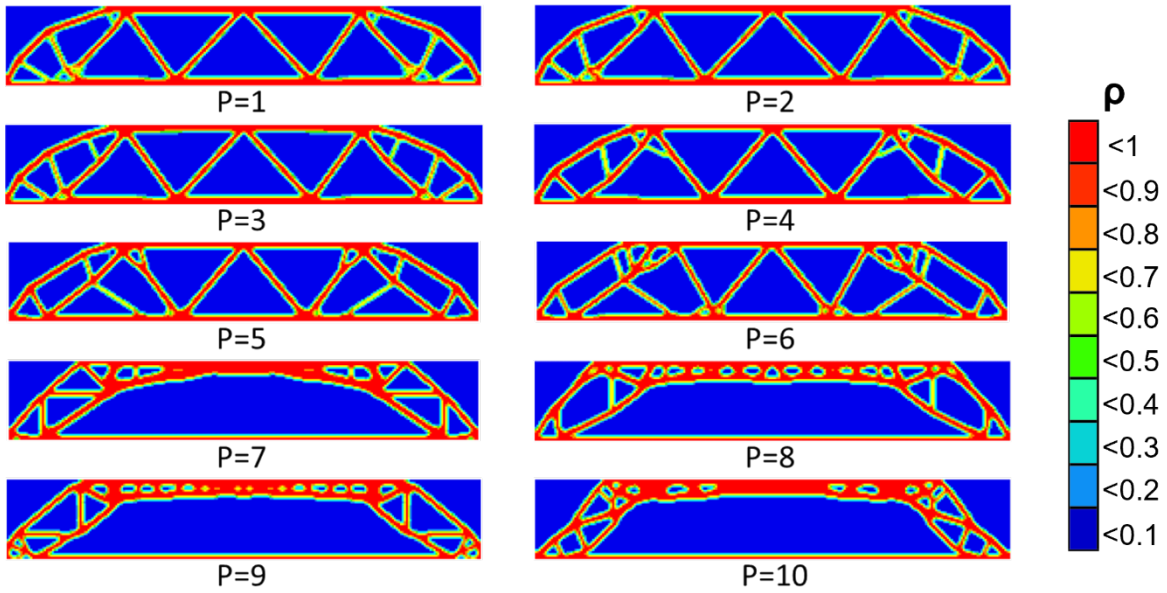


Figure 8 - Qualitative MMO result with variation of the penalty factor

Overall, penalty factors below the sudden increase in compliance should be preferred. Reducing the penalty factor leads to lower compliance values and thus to higher structural stiffness. At the same time, low penalty factors are theoretically associated with lower discreteness of the resulting topology, since elements with intermediate density values are penalized less strongly. However, an improved formation of discrete structures through an increase in the penalty factor can only be observed to a limited extent. Even for very high penalty factors, the boundary regions of the structure remain diffuse. This represents a difference compared with SMO. Furthermore, MMO already provides largely discrete topologies at low penalty factors, without pronounced grey regions or checkerboard patterns. Low values can therefore be used to improve the compliance performance of the target design without substantially impairing the quality of the resulting topology.

4.5 Combined Variation of MinDim and the Penalty Factor

While MinDim controls the minimum size of structural members, the SIMP penalty factor influences the penalization of intermediate density values. Both parameters therefore affect the discreteness and morphology of the resulting topology. A separate consideration does not allow conclusions on whether changes caused by one parameter are compensated or amplified by the other parameter. To identify robust parameter combinations for MMO, a full factorial study is conducted. The qualitative results of the parameter field study are shown in Figure 9.

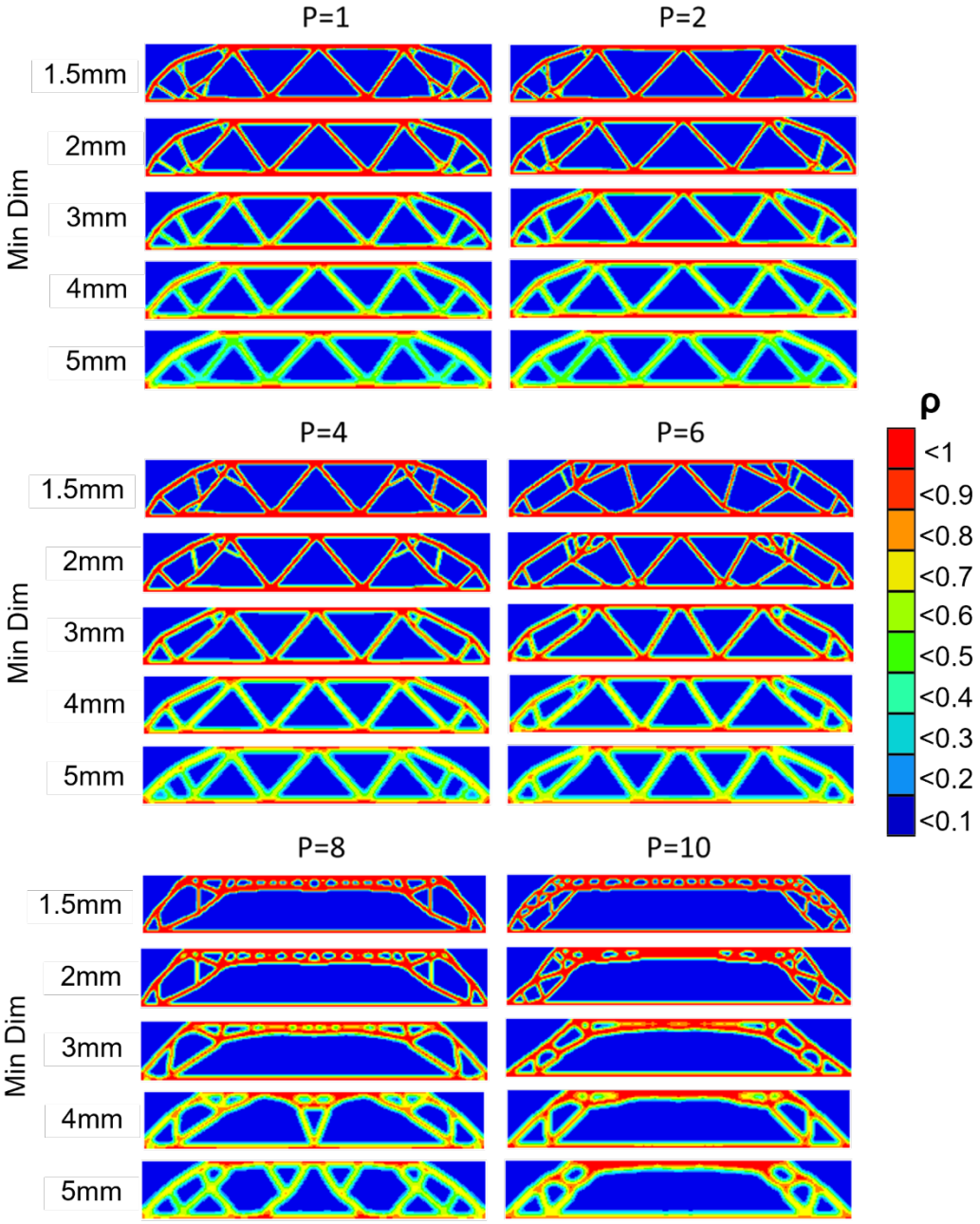


Figure 9 - Qualitative results of the MMO parameter field with variation of MinDim and the penalty factor

The qualitative assessment of the results shows that MMO produces comparable target designs for small values of MinDim and the penalty factor. However, this behavior is not maintained across the entire investigated parameter range. From a penalty factor of P = 8 onward, pronounced changes in the resulting topology occur. This effect can be observed independently of the selected MinDim value. At the same time, the influence of MinDim on the optimization result becomes more apparent. For P = 8, clearly different target designs are obtained for the investigated MinDim values.
The discreteness of the structure continues to decrease with increasing MinDim. As already observed in the individual parameter studies, the effect of high penalty factors cannot compensate for the reduced discreteness caused by large MinDim values.

To illustrate these relationships, Figure 10 shows the percentage of elements without intermediate density values within the parameter field of MinDim and the penalty factor. The analysis was limited to the parameter combinations listed in Table 1, with linear interpolation assumed between these points.

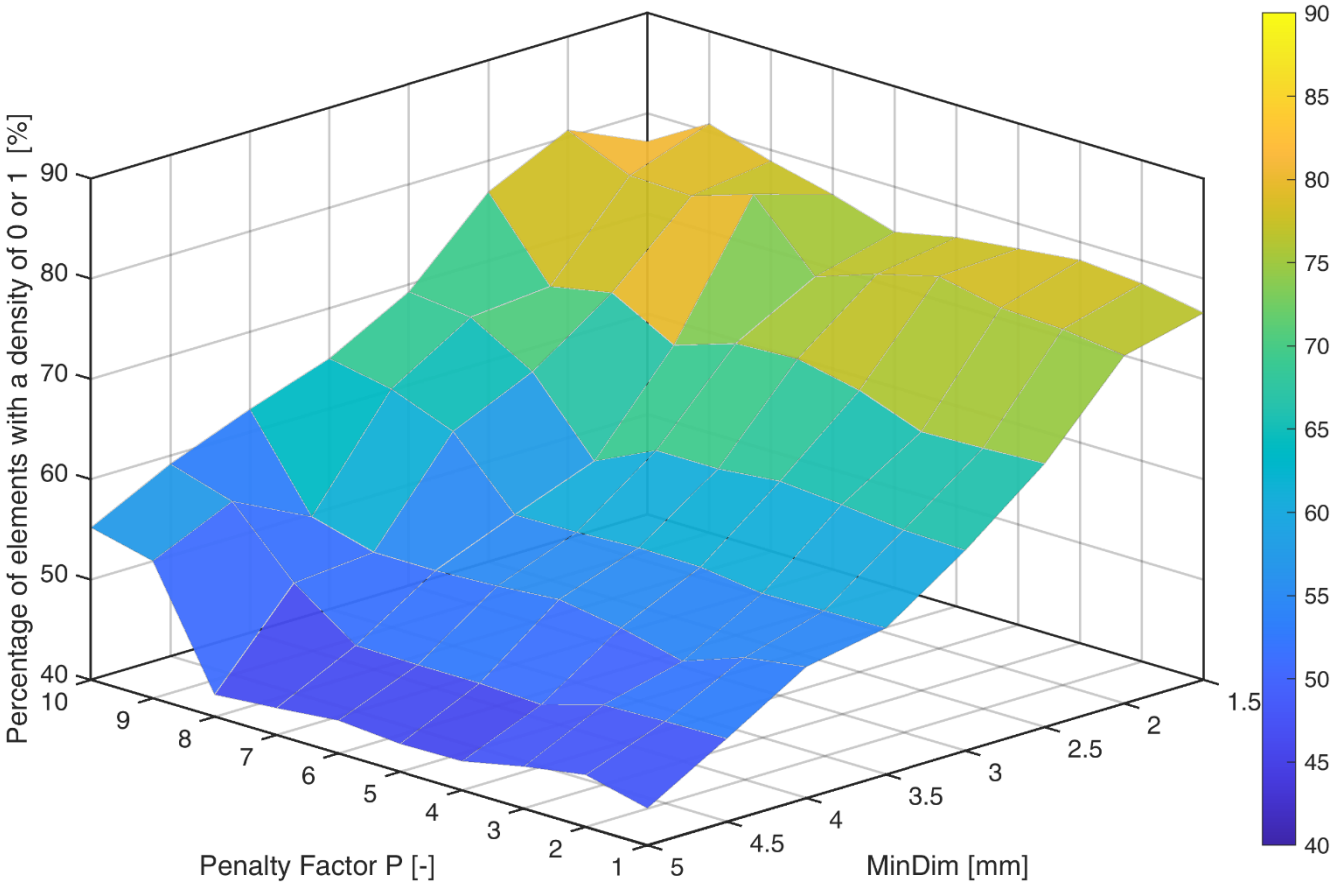


Figure 10 - Percentage of elements with a density of 0 or 1 in the final structure as a function of MinDim and the penalty factor

An almost continuous increase in this percentage can be observed with decreasing MinDim. In contrast, increasing the penalty factor at a constant MinDim value has only a minor influence on the discreteness of the structure. Thus, even without active penalization (P = 1), a largely discrete result can be obtained in the MMO. Compared to SMO this marks a difference, since usually a penalty factor of three for 3D objects is considered optimal [33]. MinDim has a stronger influence on the discreteness of the structure and should therefore be selected carefully. The results indicate that the discreteness of the resulting topology is primarily governed by MinDim, whereas the influence of the penalty factor is comparatively small. For the parametrization of the MMO, particular attention should therefore be paid to MinDim, which should be chosen as small as possible within the numerical and methodological constraints of the model.

The compliance results for the MMO are shown in Figure 11. The analysis is limited to a section between P = 1 and P = 5 and a MinDim range between 1.5 mm and 4 mm. Larger values distort the evaluation due to a pronounced increase in compliance. Therefore, the focus is placed on the lower parameter range.

The best-performing design is obtained without an active penalization function and with the smallest MinDim value. Considering both compliance and discreteness, MinDim and the penalty factor should be kept as low as possible in the MMO, since this parameter combination provides the best performance while maintaining sufficient discreteness.

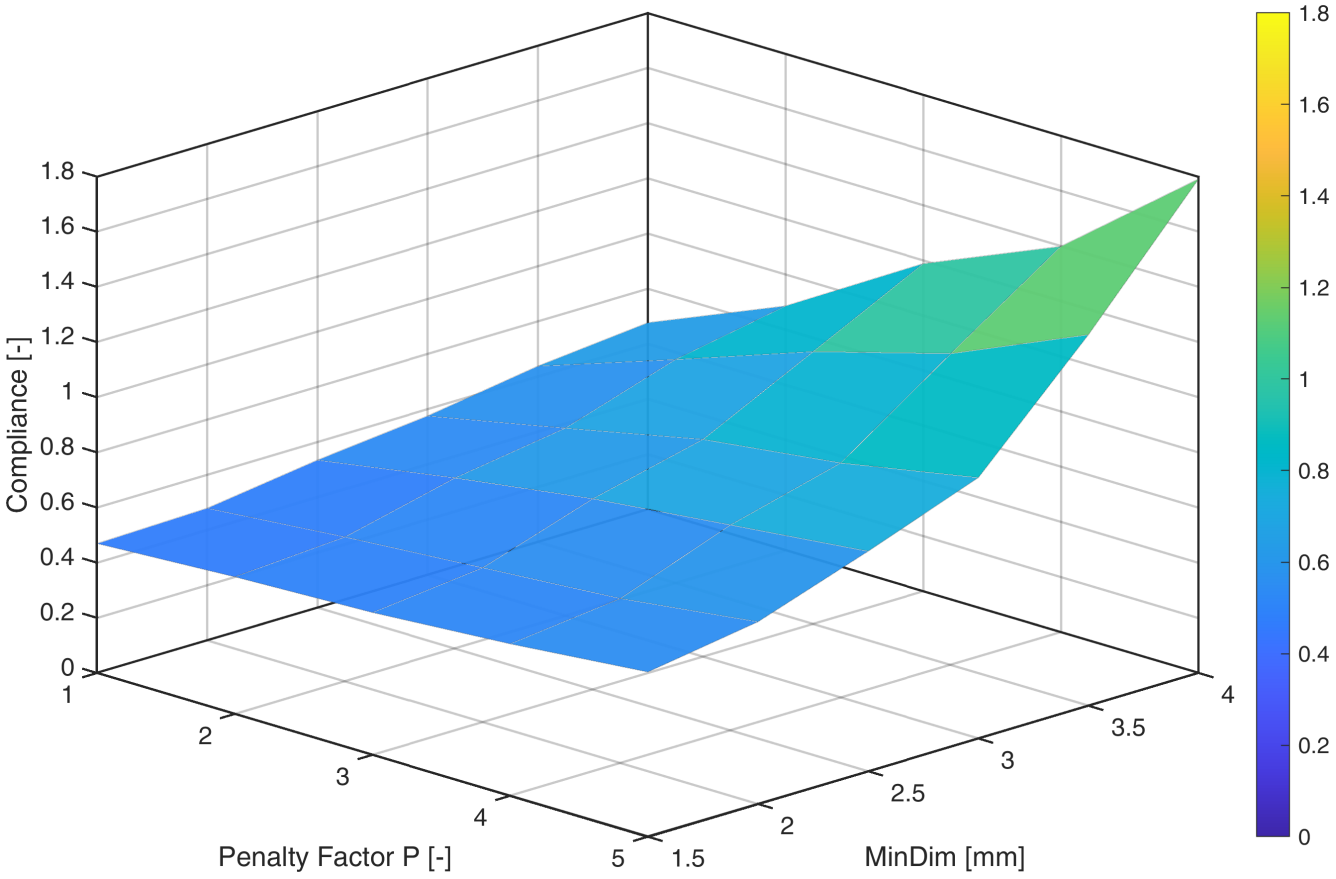


Figure 11 - Compliance parameter field with simultaneous variation of MinDim and the penalty factor, parameter range from MinDim 1.5 mm to 4 mm and penalty factor P=1 to P=5

4.6 Application of MMO Best Practices to the MBB Beam

Based on the preceding findings, a final multi-model optimization is performed. In this MMO, the insights gained from the parameter study are applied. A volume fraction of 30 % is selected, as this value lies sufficiently within the plateau region of the compliance curve and therefore enables a reduction in material usage while maintaining only a limited increase in compliance. The average element size is set to 0.5 mm, since this resolution provides a sufficiently detailed representation of the main load paths while keeping the computational effort within a reasonable range. For MinDim and the SIMP penalty factor, the lowest investigated values are selected, namely MinDim = 1.5 mm and P = 1. This parameter combination showed the best compliance performance in the previous study while still providing a largely discrete topology. The resulting design is shown in Figure 12.

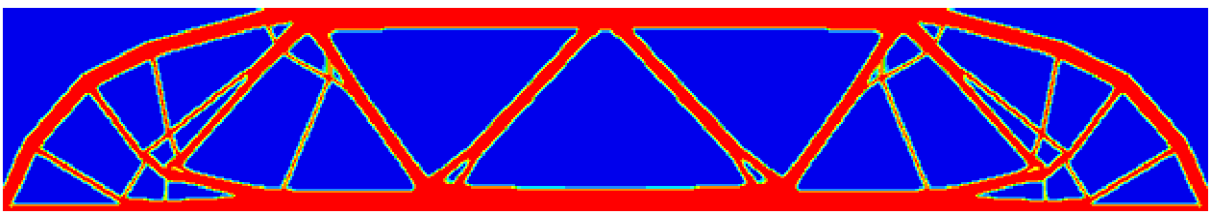


Figure 12 - Result of the MMO with adapted parameters (average element size = 0.5 mm, MinDim = 1.5 mm, penalty factor = 1)

Qualitatively, the resulting topology is characterized by clearly defined load paths and only a limited number of elements with intermediate density values. The main structural members connect the support regions with the three possible force application points and form a fine truss-like network. Compared with the parameter studies using larger MinDim values or higher penalty factors, the resulting topology

shows a more distinct material distribution and fewer diffuse regions. This indicates that the selected parameter combination is suitable for generating a common MMO target design for the investigated load scenarios.
To provide a quantitative reference, additional SMO simulations are performed. These include one SMO with a combined load case and separate SMO simulations for each individual load case. For the combined-load-case SMO, the three load scenarios shown in Figure 3 are applied to a single model and weighted equally. The same parameter settings as in the final MMO are used. This comparison corresponds to the scenario selected in Figure 2, in which a constant design space is combined with multiple load scenarios. The combined-load-case SMO serves as the direct reference for the MMO, since both approaches consider the same three load scenarios within one optimization setup. The individual SMO results, in contrast, represent load-case-specific optima and therefore provide a best-case reference for the achievable compliance in each separate load case.
The compliance values for the different simulations are summarized in Table 2.

Table 2 - Compliance values of the adapted-parameter MMO compared with the combined-load-case SMO and individual SMO results

	Compliance for load a)	Compliance for load b)	Compliance for load c)
Adapted parameter MMO	0.26	0.40	0.26
Combined load case SMO	0.25	0.39	0.25
Individual SMO	0.21	0.37	0.21

The results show that the MMO achieves compliance values close to those of the combined-load-case SMO reference. For the central load case, which represents the highest compliance value in both approaches, the deviation between MMO and combined-load-case SMO is below 2 %. For the lateral load cases, the deviation is slightly higher, but remains within a comparable range. This indicates that the MMO can achieve a structural performance close to the combined-load-case SMO while maintaining the methodical advantage of a multi-model formulation.
Compared with the SMO results optimized for individual load cases, larger differences can be observed. For the central load case, the MMO leads to an increase in compliance of approximately 9 %. The results indicate that MMO offers potential for modular lightweight design problems in aerospace-related applications, although further investigations using representative aircraft cabin structures are required. However, they also show that the selection of load cases and components to be combined within one optimization must be carefully evaluated in order to maintain an acceptable trade-off between component commonality and lightweight performance.

5. Conclusion and Outlook

This paper investigated the potential of Multi-Model Topology Optimization as a design support method for modular lightweight aircraft cabin structures. The underlying motivation was the conflict between modularization and lightweight design. While modular product architectures support component commonality, reuse and reduced internal variety, lightweight design typically leads to load-case-specific solutions with limited transferability to other variants. MMO addresses this conflict by linking corresponding design variables across multiple structural models and thereby generating a common topology for different load scenarios.
The results show that MMO is capable of generating a common load-path-oriented topology for multiple load scenarios. The variation of the volume fraction demonstrated that low material fractions are insufficient to form continuous and sufficiently discrete load paths for the investigated setup. With increasing volume fraction, the load-bearing structure becomes more pronounced and compliance decreases. However, from a volume fraction of approximately 30 %, the compliance curve begins to reach a plateau. This indicates that additional material above this range only provides a limited improvement in stiffness. A volume fraction of 30 % was therefore selected for the final MMO, as it

provides a suitable compromise between material reduction and structural performance.
The investigation of the mesh resolution showed that the fundamental topology remains largely unchanged over the investigated element sizes. The main load paths and the characteristic truss-like structure are reproduced for all mesh resolutions. However, coarser meshes lead to less distinct structural boundaries and a higher occurrence of intermediate density regions. In addition, the formation of additional struts with increasing mesh resolution could only be observed between element sizes of 1 mm and 0.5 mm. A further reduction of the element size did not lead to additional structural branching in the investigated setup. This indicates that the influence of mesh resolution in MMO may differ from observations reported for SMO, although further investigations with higher element numbers are required to confirm this effect.
A particularly relevant finding is the influence of Minimum Member Size Control. Increasing MinDim led to a higher proportion of elements with intermediate density values and thus to a less discrete material distribution. In addition, MinDim had a strong effect on the compliance values of the MMO. Larger MinDim values restricted the formation of efficient load paths and resulted in increased compliance. In the investigated setup, small MinDim values therefore provided the best combination of structural performance and sufficient discreteness.
The variation of the SIMP penalty factor showed that low penalty factors lead to lower compliance values and therefore to higher structural stiffness. In conventional SMO, higher penalty factors are often used to promote discrete topologies by penalizing intermediate densities. In the present MMO study, however, increasing the penalty factor improved discreteness only to a limited extent. Even for high penalty factors, diffuse boundary regions remained visible. At the same time, high penalty factors caused pronounced changes in the topology and a strong increase in compliance. The combined investigation of MinDim and the penalty factor showed that the discreteness of the topology is primarily governed by MinDim, while the influence of the penalty factor is comparatively small.
The comparison with an SMO using a combined load case showed that the MMO achieved comparable compliance values. Compared with SMO results optimized for individual load cases, however, larger differences occurred. This difference reflects the compromise character of MMO. While individual SMO provides the best solution for one specific load case, MMO intentionally sacrifices part of this load-case-specific optimum in order to obtain a common topology that can be used across several load scenarios.
Overall, the results indicate that MMO offers considerable potential for modular lightweight design in aircraft cabin applications. It enables the generation of common structural layouts while maintaining a structural performance close to conventional optimization approaches for combined load cases. This makes MMO particularly relevant for early design phases, where decisions on modular architectures, interfaces and component commonality strongly influence later development effort. At the same time, the results show that MMO should not be applied without careful selection of the combined load cases and components. The achievable benefit depends on whether the loss in lightweight performance remains acceptable compared with the gain in commonality and reuse.
The study is subject to several limitations. The investigations were carried out using a simplified two-dimensional benchmark model with a constant design space. This setup was deliberately chosen to enable a controlled comparison with SMO and to isolate parameter effects. However, real aircraft cabin structures are characterized by more complex geometries. In addition, only selected topology optimization parameters were investigated. Further parameters may also influence MMO results.
Future work should therefore extend the presented analysis to more representative aircraft cabin structures and varying design spaces. In addition, future investigations should consider three-dimensional models, more complex load combinations and realistic boundary conditions derived from cabin applications.

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